THE PALAEOECOLOGY OF A TRANSITION ZONE ACROSS AN UPPER CRETACEOUS BOUNDARY IN NEW JERSEY

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ABSTRACT. Sediments and fossils were sampled at one-foot intervals across the Mt. Laurel–Navesink boundary (Upper Cretaceous) at Marlboro, New Jersey; this sequence is of some interest as it contains the *Exogyra cancellata* Zone, which has been traced along the coastal plain from New Jersey to Texas. It is shown that weak bottom currents were present during the time represented by this sequence, that the oysters and sponges examined lived in non-turbid waters of normal salinity in which nutrients were provided in quantity, that water depth increased in the upper part of the sequence, and that an important break in sedimentation, indicated by electron microphotographs of the surface textures of sand grains and the presence of shallow-water crabs, is found at the Mt. Laurel–Navesink boundary and possibly represents a disconformity. Interlocked oyster shells with sponge borings found throughout the section indicate local periods of water turbulence followed by long periods of quiescence. Comparison of sediment and individual size frequency distributions implies that *Guembelina ultimatumida* was probably sorted by water currents after reaching the sea bottom.

THE study of changes in the biological and physical characteristics of sedimentary rock over small stratigraphic intervals has recently received impetus from the work of Carozzi (1958) and Carozzi and Zadnik (1959), who demonstrated that stratigraphic micro-environmental studies of consolidated carbonate rocks are of fundamental importance in the reconstruction of ancient environments, since numerous sedimentation processes are of small scale and therefore commonly overlooked. Relatively unconsolidated deposits of the type discussed below can be similarly studied.

We have attempted to obtain as much environmental information as possible from the megafossils, microfossils, and sediments over an interval of 14 feet in the Cretaceous Navesink and Mt. Laurel greensands at Marlboro, New Jersey. Two other localities at similar stratigraphic horizons were studied to supplement the Marlboro data (text-figs. 1 and 2).

Carozzi (1958) indicated that a fully oriented sample taken every foot vertically appears to be sufficient for investigations of both lithologically uniform and variable sequences. We sampled sediments and fossils at one-foot intervals across the Mt. Laurel–Navesink boundary at Marlboro; the samples near the contact were taken at 6-inch intervals (Table 1). This particular sequence is of interest as it contains the *Exogyra cancellata* Zone, which has been traced along the coastal plain from New Jersey as far west as Texas (Stephenson 1933); it is extremely fossiliferous and contains both mega and microfossils. Weller (1907) pointed out that the entire Upper Cretaceous sequence in New Jersey shows an alternation of two faunal types: the '*Lucina* fauna', considered to be a shallow shelf fauna, and the '*Cucullaea* fauna', considered a deeper water association. The Mt. Laurel–Navesink sequence, dealt with here, was considered by Weller to represent the deeper water '*Cucullaea* fauna'.

Our results indicate that within the stratigraphic interval studied the water probably varied from shallow to deep shelf depth. Four approaches were used in an attempt to
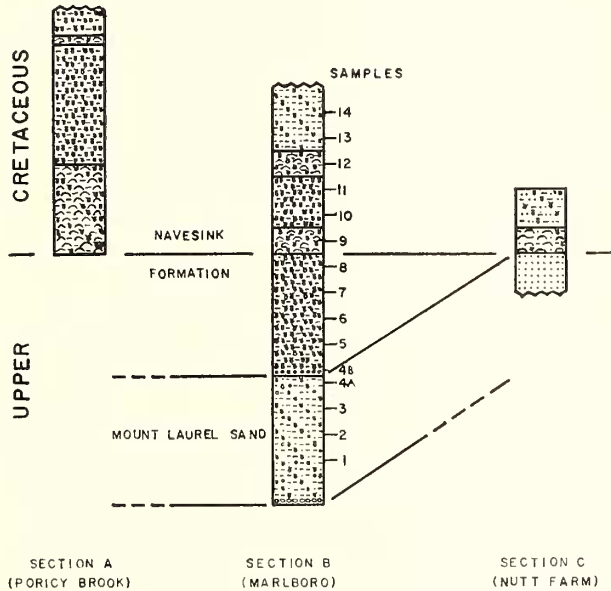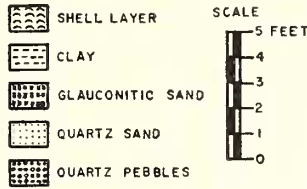
delineate environmental conditions: analyses of megafossils, microfossils, sediments, and electron microscopic sand surface textural studies, all of which are discussed below.

The Mt. Laurel–Navesink sands of New Jersey are Upper Cretaceous unconsolidated greensands containing variable amounts of silt and clay. They dip at very low angles to the south-east and were probably deposited under relatively stable shelf conditions.
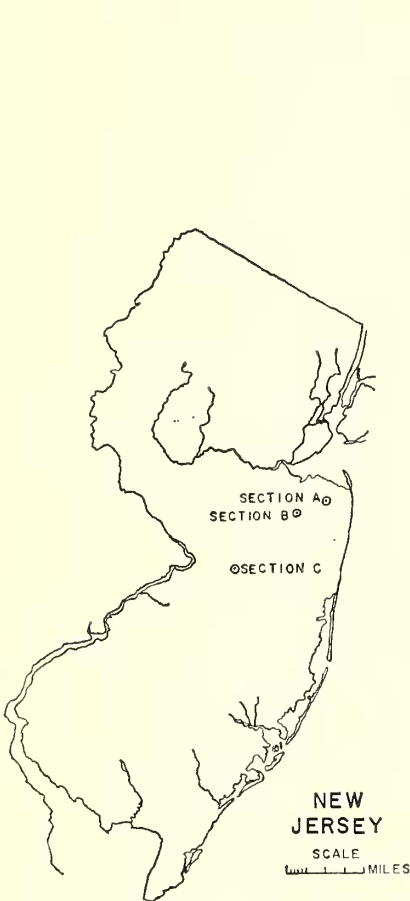
TEXT-FIG. 1. Location of sections.   TEXT-FIG. 2. Stratigraphic details of sections.

The Mt. Laurel sand dips 25 feet per mile to the south-east in Monmouth County, New Jersey, and varies in thickness from 5 to 15 feet (Spangler and Peterson 1950). It is a marine glauconitic, medium to coarse, pebbly, buff, red, yellow, or black sand and may locally contain varying amounts of clay. At the Marlboro locality (1·2 miles east of Marlboro, New Jersey, in the south bank of Hop Brook) it consists of 5 feet of grey to olive-green, pebbly, glauconitic, sandy clay with *Belemnitella americana* (Morton), sharks' teeth and crab claws. A good deal of scattered, white crumbly calcium carbonate present represents the remains of shells which have partially gone into solution.

The contact between the Mt. Laurel and the overlying Navesink occurs between our samples 4A and 4B; the boundary is marked by a zone containing crab claws at the very

top of the Mt. Laurel and a large number of small pebbles an inch or two below. The basal contact of the Mt. Laurel with the underlying dark, micaceous Wenonah clay is clearly exposed.

The Navesink sand dips about 20 feet per mile to the south-east where it is best developed in Monmouth County, New Jersey, and locally attains thicknesses of 30 feet (Spangler and Peterson 1950). It is a marine, black to green, glauconitic sandstone containing varying amounts of clay. The lower part of the Navesink at Marlboro contains three fossiliferous zones, a lower *Belemnitella* zone, a middle *Exogyra* zone, and an upper *Gryphaea* zone. At most other localities, the three zones are combined into a single shell layer. The Navesink at Marlboro is about 26 feet thick, but the upper contact is obscure and seemingly gradational. It is overlain by a few feet of yellowish, non-glauconitic sand which may be the base of the Red Bank formation.

At another locality about 7 miles away, on the south bluff of Poricy Brook, $\frac{1}{2}$ mile south of Oak Hill, and about $1\frac{3}{4}$ miles south of Middleton, New Jersey, about 17 feet of Navesink sand are found, including the *Exogyra* and *Gryphaea* layers. The lithology of the Navesink here is very much like that at Marlboro.

The third locality studied, which is in a tributary to Crosswicks Creek, $\frac{1}{3}$ mile north of the C. B. Nutt Farm on Arneytown Road, near Arneytown, New Jersey (about 23 miles south-west of the Marlboro area), consists of a grey, glauconitic sand with numerous fossils. Here the three layers found at Marlboro are combined into one; the material may be considered coquina-like in nature. Lowenstam and Epstein (1954) collected *Belemnitella americana* for their oxygen isotope studies on Cretaceous palaeotemperatures in Crosswicks Creek less than a mile from this locality.

METHODS

A channel was excavated to a depth of 6 inches in the vertical sections sampled. The samples were carefully removed from between $1\frac{1}{2}$ inches above and below every one-foot marker. At Marlboro, sampling began $3\frac{1}{2}$ feet below the Mt. Laurel–Navesink contact and ended 10 feet above it. Samples were taken every foot except near the contact, where 4A and 4B were sampled 6 inches apart. Approximately 500 grams of material was collected at each level; each sample was thoroughly mixed in the laboratory, and quartered until a representative 5-gram sample for foraminiferal examination was obtained. A second 5-gram sample was taken from two of the channel samples and examined for foraminifera as indicated below. There were no significant differences in foraminiferal content in either of the two additional 5-gram samples examined as compared with the original samples.

In order to deflocculate the clay in the sediment and to free the microfossils, each 5-gram sample was soaked in sodium carbonate solution for thirty minutes; the mixture was then heated over a bunsen burner for the same length of time. Clay was removed by wet sieving through a 230-mesh sieve. The remaining material was washed into porcelain evaporating dishes for drying.

Samples 1–14 (Marlboro) were dried over a bunsen burner, while the Poricy Brook and Crosswicks Creek samples were dried in an oven at about 100° C. Poricy Brook samples contained a large amount of non-disaggregated clay after this treatment; they were then placed in sodium carbonate solution, ultrasonically vibrated for about five

minutes, sieved and dried at 100° C. The fossils were floated off on carbon tetrachloride which was poured on to filter paper; the organisms were then transferred from the filter paper to micro-slides ruled into sixty squares. The heavy fraction was examined for additional foraminifera after carbon tetrachloride flotation. No additional foraminifera were noted in samples 1–6 and 14; no more than fifteen foraminifera were found in samples 7–13. It is apparent from Table 1 that the latter number is insignificant when compared with the large number of foraminifera previously obtained in samples 7–13.

TABLE 1

Layer	Total no. of foraminifera in 5-gm. sample	% Plankton	Benthonic-planktonic ratio	Species number P	Species number B	Genera number P	Genera number B	Skewness SK	Sorting SO	Max. quartz grain size (inches)	% CaCO₃ by weight	
14	13	46	1·20	3	4	2	4	0·70	2·75	0·04	7·8	
13	27,946	69	0·44	6	13	5	13	1·48	4·85	0·04	10·6	
12	22,088	85	0·18	6	16	5	14	1·44	4·84	0·05	27·2	Gryphaea
11	30,516	85	0·18	8	23	5	20	1·42	4·69	0·05	20·9	
10	28,993	84	0·20	10	28	5	25	1·01	3·32	0·07	21·3	
9	21,135	82	0·23	6	26	4	24	2·29	6·16	0·09	30·0	Exogyra
8	13,460	82	0·22	5	18	4	16	1·48	4·36	0·07	17·4	
7	12,172	71	0·40	7	19	5	14	0·64	2·33	0·06	10·2	
6	103	54	0·84	4	11	4	9	0·22	1·69	0·06	3·5	
5	9	78	0·29	3	2	2	2	0·24	1·76	0·05	1·8	
4B	1	0	—	0	1	0	1	0·19	1·73	0·10	5·3	Crabs, Vs
4A	209	70	0·41	7	12	4	11	0·80	2·68	0·18	11·1	No Crabs, no Vs
3	4	25	3·00	1	3	1	3	0·16	1·77	0·12	10·0	
2	4	75	0·33	2	1	2	1	0·23	1·85	0·15	12·1	
1	22	54	0·83	3	4	2	4	0·00	1·54	0·12	5·9	

All samples were taken at one-foot intervals, except 4A and 4B, which are 6 inches apart.

All foraminifera in samples 1–6 and 14 were picked and identified, counted and measured with a micrometer disk attached to a binocular microscope. A sample slide was prepared with representative species from these samples.

The foraminifera in samples 7–13 (5-gram samples) were split to either one-quarter or one-eighth for convenience. Total plankton and benthos in all samples from each locality were counted and recorded. All species were also counted, and two measurements (maximum length and width or, in the case of approximately spherical organisms, maximum diameter of entire organism and of last chamber) were made on individuals of each of the following species: *Guembelina striata* (Ehrenberg), *Guembelina ultimatuuuida* White, *Globigerina lacera* (Ehrenberg), *Globigerinella aspera* (Ehrenberg), *Guttulina adhaerens* (Olszewski), *Globulina lacrima* Reuss, *Pseudouvigerina seligi* (Cushman), and *Buliminella fusiformis* Jennings. The figures were then mutiplied by the appropriate factor (4 or 8). Table 3 is a record of the total figures.

The foraminifera in all the samples showed some breakage; a considerable amount of shell debris was present in the residue remaining after carbon tetrachloride filtration. An experiment was planned in which foraminifera picked from untreated sediment were

to be mixed with unfossiliferous material from sample 4B and then subjected to the foraminiferal separation procedure outlined above. However, it was impossible to obtain enough specimens without subjecting the fossiliferous sediment to treatment which might break some of the more fragile specimens. Thus no estimation of breakage due to the techniques used could be made.

PALAEOECOLOGY OF MEGAFOSSILS

The most common oysters at Marlboro are *Gryphaea convexa* (Say), *Exogyra costata* Say, *Exogyra cancellata* Stephenson, *Ostrea mesenterica* Morton, and *Ostrea falcata* Morton. The section examined includes three major shell layers, all in the Navesink formation. The uppermost is known as the *Gryphaea* bed, several feet below is the *Exogyra* bed and about 3 feet below that is the *Belemnitella* bed (Table 1 and text-fig. 1). The beds are separated from each other by sediments which contain fewer fossils. Each of the shell beds contains all the species listed above, but the number of individuals varies from one bed to another.

In the *Exogyra* layer, little evidence of abrasion was noted, although solution was particularly evident. Examination of a layer about 200 yards downstream showed that solution was probably post-depositional; here the oysters were quite fresh and little evidence of solution was present. Nests of *Exogyra* were found with some single valves interlocked, suggesting local turbulence. However, since many larger isolated shells were found with their valves in life position, currents must have been generally aperiodic and very local.

In one of the interlocked nests, the surface of the innermost interlocked shell was found to contain sponge borings; these borings could not have occurred while the shells were interlocked. Thus the bored shell probably lay exposed on the bottom for the length of time necessary to permit boring sponges (*Cliona sp.*) to grow, was moved a short distance and interlocked, which indicates relatively long periods of calm followed by short periods of turbulence. Similar situations were noted in other localities throughout the Navesink formation.

Portions of the *Exogyra* layer were white with high concentrations of calcium carbonate; small *Exogyra* shells were rare and it is possible that solution removed a good deal of the shell material. Although in certain epifaunal marine communities the presence of adults may prevent larvae of the same species from settling, which would cause all specimens taken to be of approximately the same size (see discussion in Thorson 1957, pp. 483–4), this is probably not the case here; at the Crosswicks Creek locality (of roughly equivalent age) adults and young of a presumably living and indigenous population were found together. Fragile specimens of less than half an inch diameter, through a graded series to thick-shelled forms of the same species as large as 6 inches in diameter with both shells together, were found at the latter location.

The size and thickness of both *Exogyra* and *Gryphaea* at all localities examined are rather unusual; specimens over an inch thick and with a maximum diameter of over 6 inches were found. Sponge borings were usually seen only on the larger specimens of *Exogyra* and *Gryphaea*; the frequency of boring was less on the right than left valves and more borings were found on the outsides of both valves than inside. Some valves had borings which started from the interior but did not reach the exterior, indicating that at

least some shells were bored after death; however, many of the borings may have occurred before death, as modern *Cliona* bores living oysters. The surfaces near the margins of the left valves contained the least concentration of borings while the highest concentrations were found in the central portions. Since the left valve was either fastened to the substratum or the oyster was lying free upon it in life, it is assumed that these valves were overturned to permit boring sponges to grow (text-fig. 3). A number of specimens with both valves together, relatively free of sponge borings, were found in living position, indicating probable burial in place.
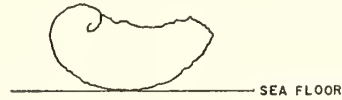
Belemnitella americana is found in the upper part of the Mt. Laurel and in the lower and middle parts of the Navesink. At Marlboro it occurs scattered through the portion of the sequence represented by samples 1–12 and is well preserved. Usually the rostrum is the only portion of the organism seen and there is no evidence of solution; occasionally, however, portions of the aragonitic phragmacone can be observed in various stages of solution. Cornish and Kendall (1888) believed that the rostrum of belemnites was composed of calcite; Bøggild (1930) showed that the phragmacone of *Atractites*, a projection of the shell that contained the air chambers, was probably composed of aragonite.

EXOGYRA   COSTATA

A. SIDE VIEW OF LEFT VALVE IN LIVING POSITION
(DIAGRAMMATIC)

DOTS INDICATE
AREAS BORED

B. BOTTOM VIEW OF LEFT VALVE SHOWING CONCENTRATION
OF SPONGE BORINGS (DIAGRAMMATIC)

TEXT-FIG. 3. Borings in *Exogyra costata*.

In moving water, cones tend to be oriented with their long axes in the direction of maximum current movement (Petřánek and Komárková 1953). Compass orientations of 40 belemnites were made over a stratigraphic interval of one foot directly above the Mt. Laurel–Navesink boundary at Marlboro, New Jersey; no overall preferred orientation was found. Several groups of belemnites with tips pointing in the same direction were found close to casts of numerous pelecypod shells and it is possible that the shells served as obstacles against which belemnites accumulated. The orientation of belemnites around obstacles indicates that currents were present, but lack of overall orientation and the fact that a great deal of bottom scouring did not occur (very few belemnites were uncovered and exposed to boring sponges for any length of time—see below) would tend to show that these currents were extremely weak.
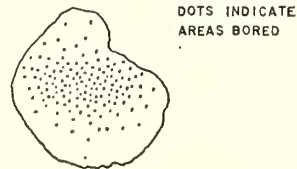
Belemnites were not significantly bored by *Cliona*; only 5 out of 200 specimens observed were so bored and in another group of 8, only one which was oriented with its tip pointing up contained borings on the apical inch of its 6-inch length. The associated non-vertical specimens were not bored. Possibly the tip of the vertical specimen was exposed above the sediment surface for the length of time necessary for boring to occur. This occurrence may be related to the rate of sedimentation.

Belemnites from the Navesink have been used for isotopic temperature determinations since the density of the rostrum precludes much ionic movement. Temperatures at which organisms at the base of the Navesink formation precipitated their shell material

ranged from 16·4° C. to 20·5° C. (Lowenstam and Epstein 1954). The base of the Navesink at Crosswicks Creek would roughly correspond to samples 7–13 at Marlboro, New Jersey. It is of interest to note that a temperature range of 17° C. to 22° C. at 50 fathoms (300 feet) characterizes bottom waters in the Gulf of Mexico at the present time (Bandy 1956).

In sample 4B a crab-claw layer (*Protocallianassa mortoni*) marks the top of the Mt. Laurel formation. The carapace material found was fragmented; however, a few of the claw segments and pincers were articulated. The segments occur in hard concretionary masses cemented with calcium carbonate; frequently the masses contain a great deal of limonite or goethite which probably originated from the weathering of glauconite. Egg-shaped to irregular in form, the concretions are harder than the surrounding matrix and increase in hardness as the outside layers are stripped away. The segments disintegrate upon soaking in distilled water; high concentrations of calcium carbonate but no glauconite grains are found inside the claws. Occasionally white concretions are observed which are shaped like crab claws except that the segments themselves are missing; this suggests removal after deposition. The claws may be oriented in one direction within a single concretion suggesting movement by currents before formation. Most crab segments are black, but brown patterns which are apparently original can be seen on several specimens.

The claws were probably covered and cemented with calcium carbonate before they could disintegrate or disarticulate and were then transported a very short distance (many concretions can be seen with crab claws exposed and unabraded). The fact that the carapaces are not found whole would suggest that they disintegrated somewhat faster than the claw segments; differential sorting seems unlikely, since the preserved segments are of many different sizes. The sediment in sample 4B, the crab-claw layer, differs considerably from the layer below it in terms of skewness, sorting and maximum quartz grain size (Table 1). It is possible that sample 4B represents a lag deposit, with the fine material having been removed. Crab-claw concretions and one foraminifer are present in addition to a layer of pebbles immediately below; the smallest silt–clay to total weight ratio in all samples examined is also found. We conclude from all the evidence that there is a strong possibility of a disconformity here. Layers with numerous crab claws may represent shoaling even in formations which are generally described as having been deposited in deeper water.

In the Upper Cretaceous *Protocallianassa* has been found in the Merchantville, Wenonah, Mt. Laurel, Navesink, and Tinton formations, all of which are thought to have been deposited in deep water except for the Wenonah, which may have been deposited in shallow water (Henry B. Roberts, *in litt.*). However, in sample 4B numerous claw fragments are found in a sediment which was certainly deposited in shallow water; only one foraminifer was found in this layer and the surface textures of sand grains examined with the electron microscope (see below) indicate beach action. *Callianassa* today occurs generally at depths of 5 to 50 fathoms (De Man 1928) or even less, and lives on sandy or muddy bottoms near the coast. Most modern species tend to live at the minimum rather than the maximum depth. Stevens (1928, 1929) has studied the Callianassidae from the Puget Sound, Washington, area and has shown that several species are destructive to oyster fisheries, as oysters are smothered by material thrown up by the crabs in the process of digging their burrows. It is interesting to note in this connexion

that oyster shells are usually not found with numerous crab remains; at Big Brook the crab-claw layer is barren of oyster shells.

The presence of numerous *Cliona* (class Demospongea) borings in many of the larger oyster shells and several of the belemnites is also interesting, as sponges are good ecological indicators, chiefly with reference to depth, salinity, and lack of turbidity. *Cliona* suggests moderate depths, generally greater than 60 feet but less than 600 feet; it flourishes especially well in areas of sea offshore from mouths of rivers. *Cliona* usually requires clear, silt-free water and full oceanic salinity (De Laubenfels 1953, 1957). De Laubenfels (1936) also believes that if a stratum or horizon contains many fossil sponges it is likely, although not certain, that it was deposited in relatively silt-free water.

All the above would suggest that the water in which the organisms at Marlboro lived was of normal oceanic salinity, and free from turbidity; the oysters were located where nutrients were provided in quantity and lived at depths somewhere between 60 and 600 feet. Other types of information elsewhere in this paper also support these conclusions.

At Poricy Brook, the crab-claw layer is below brook level, while at Crosswicks Creek a few crab claws have been found scattered among the oysters and belemnites. This locality also contains scattered *Belemnitella americana*; the belemnite bed in most places is below brook level. At Crosswicks Creek, belemnites occur in great numbers in a coquina-like layer with numerous oysters.

MICROFOSSILS AND SEDIMENT

Fox and Olsson (1960) have indicated that the Navesink formation represents greater depth than the Mt. Laurel. They believe that the Navesink fauna, containing high percentages of species and individuals of the benthonic foraminiferal families Lagenidae, Buliminidae, Anomalinidae, and Rotaliidae, in addition to floods of planktonic foraminifera, was deposited at neritic depths of from 300 to 600 feet. We believe that the lower figure is more correct and that the water depth fluctuated from very shallow littoral to about 300 feet or less as indicated below.

Fox and Olsson (op. cit.) also infer that the large numbers of individuals present in the Navesink are related to very slow rates of sedimentation. At Marlboro the number of foraminiferal species in the Mt. Laurel is small and greatly increases in the Navesink (samples 7–13). Moreover, the increase in numbers of species is comparable to the increase in the numbers of individuals (Table 1); in some cases the trends correspond. The numbers of genera, species and individuals all change approximately together from sample to sample (Table 1). This probably occurs because a greater abundance of individuals in a sample increases the probability of finding a given species. However, the tremendous increases in individual and species abundance from samples 6 to 7 suggests increase in depth, decrease in the rate of sedimentation, or both; the reverse is true for samples 13 to 14. Bandy and Arnal (1957) reported an increase in the number of species away from shore into progressively more stable environments. Waller (1960) noted that the number of individuals increased with depth, reaching highest values on the outer shelf and decreasing somewhat beyond the break in slope.

The benthonic/planktonic ratio (B/P) is considered to be a depth indicator (Drooger and Kaasschieter 1958; Zalesny 1959; Waller 1960, and others), the lower the ratio the

greater the depth. In samples 1–6, and 14, too few foraminifera are present for the ratio to be significant; however, in samples 7–13 the number of individuals is more than adequate.

The B/P ratio decreases from sample 7 to sample 8, indicating a possible deepening of the water, and increases from sample 12 to sample 13, indicating possible shallowing. In samples 8–12 the ratio is almost constant, which would suggest a relatively constant depth.

Near-shore foraminiferal assemblages frequently include large numbers of agglutinated tests; for instance, Lowman (1949) found the greatest number of *Haplophragmoides* and *Ammobaculites* near shore in the region around the Mississippi delta. Thus these genera may indicate near-shore environments of low salinity and shallow water. The former is most abundant on bottoms between 30 and 120 feet deep. None were found in the Mt. Laurel or Navesink at the localities examined. At the opposite end of the depth range, Lowman found that the Buliminidae are the predominant family below depths of about 300 feet in the infra-neritic and inner bathyal zones. In between these depths, he noted highly diverse populations with many families and genera represented, and locally dominated by the Lagenidae, Buliminidae, and Rotaliidae (or Anomalinidae if *Cibicides* be assigned to this family following Cushman).

Abundant buliminids, lagenids, and rotalids were found in samples 7–13 at Marlboro; assuming that the genera and families found at Marlboro correspond roughly to the above definitions of microfaunal facies, the water depth in these samples could be assumed to have been somewhat greater than 120 feet but less than 300 feet, at least in the samples where foraminifera are common.

Recent work indicates that a large proportion of planktonic individuals (as at Marlboro) is not necessarily unusual in relatively shallow water. Bandy (1956) noted 70 per cent. planktonic foraminifera at slightly over 40 fathoms off St. Petersburg, Florida, and Bandy and Arnal (1957) record 25 per cent. plankton at 10 fathoms at two stations off the west coast of Central America. Burnaby (1962), who has studied the palaeoecology of the Chalk Marl (Cretaceous) in England, also believes that floods of planktonic foraminifera do not necessarily indicate depths of 200 to 300 fathoms or more.

Carter (1951) measured the total number of foraminiferal shells and the total number of individuals of several species in the 30-mesh and 30–60-mesh fractions of a number of unwashed samples from the Coralline Crag of Suffolk. He then plotted each of these measures against stratigraphic position and found that a sudden change in lithology was not reflected in alteration of the constitution of foraminiferal assemblages unless there was also a change in grain size. Neither was there a change in the ratio of foraminiferal tests to sediment. This suggested the work below.

Assuming the presence of bottom currents, any foraminifera on the bottom should be subject to sorting in the same way as other components of the sediment. A comparison of the size-frequency distributions of individual species and sediment in successively higher stratigraphic horizons might therefore show correlation, assuming, of course, that bottom currents were powerful enough to move both fractions. On the other hand, if only the planktonic foraminifera correlate with the sediment, this might suggest (but not prove) that currents were only strong enough to move foraminifera while they were still above the water–sediment interface.

Size frequency determinations were made on four species of foraminifera at the

Marlboro locality: *Guembelina ultimatumida*, *Globigerinella aspera*, *Pseudouvigerina seligi*, and *Buliminella fusiformis*. These species were chosen because upon preliminary examination they appeared to be among the most common and widely distributed. The measurements took a good deal of time and were therefore made on four species only.

PHI QUARTILE SKEWNESS (Sk $_{q\phi}$)
MARLBORO SAMPLES

Guembelina ultimatumida

Globigerinella aspera

Buliminella fusiformis

Pseudouvigerina seligi
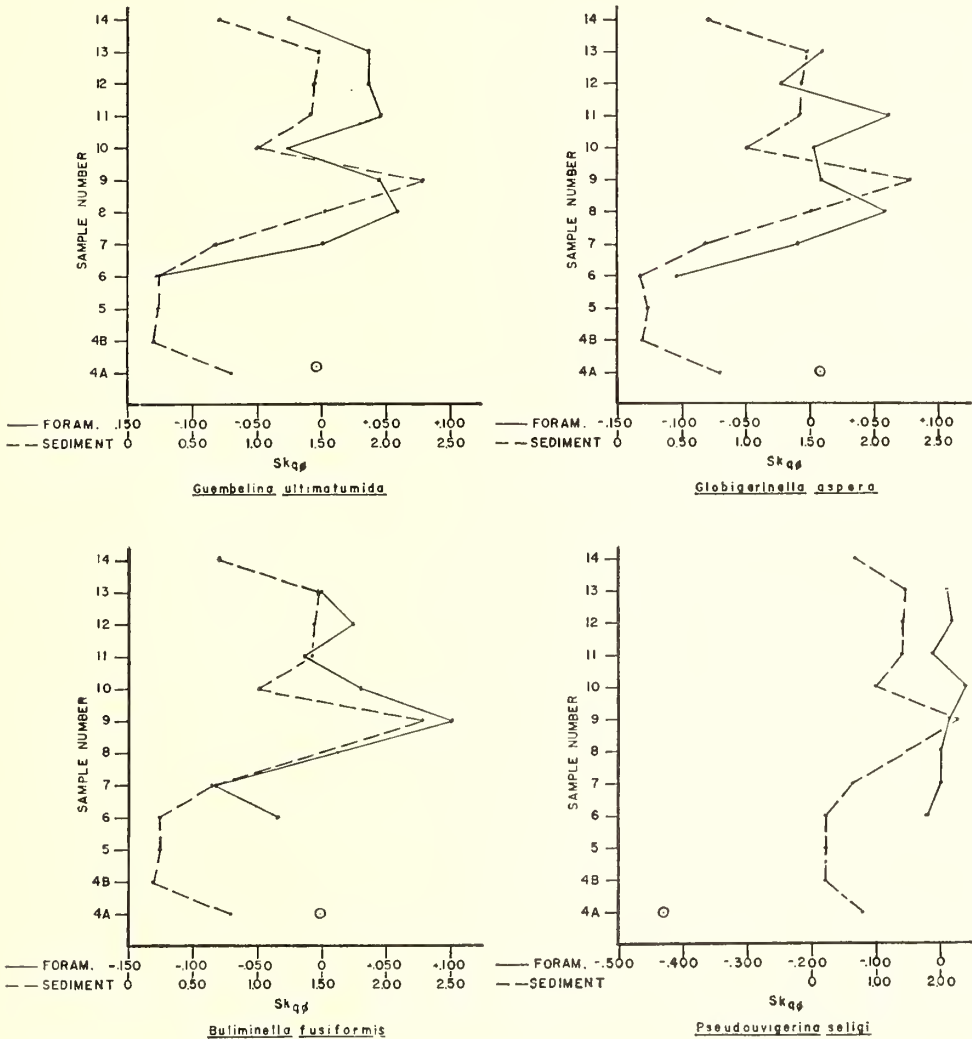
TEXT-FIG. 4

The Phi quartile skewness $\left(\frac{Q_3 - Q_1 - 2Md}{2}\right)$ was then calculated for each of these species, the same measurements being made for the sediments from which the foraminifera had been collected, and the figures compared (text-fig. 4).

Q_1 First quartile in a size frequency distribution with 75 per cent. of the material coarser than the given Phi diameter.

Q_3 Third quartile in a size frequency distribution with 25 per cent. of the material coarser than the given Phi diameter.

Md The median diameter of the distribution (note that all diameters are in Phi units).

The *Guembelina ultimatumida* (planktonic) and sediment curves correspond rather well and it should be noted that a large number of specimens of this species were measured (Table 2). *G. aspera* and *B. fusiformis* do not correspond so well and *P. seligi* corresponds very poorly to the sediment curve. *G. ultimatumida* was probably sorted after settling to the sea bottom; *G. aspera* and *B. fusiformis* may also have been sorted

TABLE 2. Number of specimens measured for size-frequency studies in each of four species

Layer	1	2	3	4	
14	4	0	0	1	
13	52	18	26	37	
12	66	25	16	18	
11	109	41	19	25	
10	128	71	34	28	
9	126	39	36	13	
8	411	35	33	30	
7	335	47	42	20	
6	23	23	27	6	
5	4	0	1	0	
4B	0	0	0	0	Navesink
4A	112	21	19	7	Mt. Laurel
3	0	0	0	0	
2	0	1	0	0	
1	7	0	0	0	

1. *Guembelina ultimatumida*   3. *Pseudouvigerina seligi*
2. *Globigerinella aspera*   4. *Buliminella fusiformis*

but the number of specimens measured is too small to decide one way or the other. *P. seligi* may not have been sorted, but again the latter argument applies.

The foraminifera in all samples were examined in detail; the maximum size varied somewhat from sample to sample as did the number of solution holes. Much less solution was noted in the foraminiferal shells than in *Gryphaea* and *Exogyra* although both foraminifera and oysters have shells of calcite. In places where large numbers of oysters were observed, the number of solution holes in the foraminifera appeared to decrease; if part of the solution occurred on the sea bottom, it is possible that the oysters served as traps for sediment moved by bottom currents and hence the length of time that a foraminifer spent in direct contact with sea-water would be reduced. Breakage also varied from one sample to another and did not seem to be directly related to solution. The numbers of species and genera also vary in samples 9–12, as do the sorting coefficients (Table 1). Thus, although the depth of water was approximately the same for samples 9–12, environmental conditions varied to some extent.

The important foraminiferal genera and species in this paper are illustrated in Cushman (1946) and Nine (1954); the macrofossils are shown in Richards *et al.* (1958).

TABLE 3. A list of all the Foraminifera found in each 5-gram sample at Marlboro, New Jersey

Layer / NAME	1	2	3	4A	4B	5	6	7	8	9	10	11	12	13	14
Quinqueloculina sp.										14					
Quinqueloculina sp.									16	14	61	249			
Spiroplectammina laevis (Roemer) var. cretosa Cushman							10								
Spiroplectammina semicomplanata (Carsey)											8	10			
Dorothia sp.				1						14		21			
Robulus sp.							1			14		21	12		
Lenticulina sp.											16				
Planularia dissona (Plummer)							10			21					
Marginulina sp.				1											
Dentalina cf. D. consobrina D'Orbigny							10				16				
Dentalina basiplanata Cushman										14	16				
Lagena lineata (Williamson)			1									21			
Lagena sulcata var. (Walker and Jacob) semiinterrupta W. Berry									11		16	21			
Guttulina adhaerens (Olzewski)			1			1	10		85	14	16				
Guttulina sp.											23	31	12		
Globulina lacrima Reuss			1			5	20		21	114	16	125	145	59	2
Globulina sp.						1			11		60	10	12		
Paleopolymorphina sp.							1			7	16				
Ramulina ornata Cushman							1			14	8				
Nonionella ansata Cushman											16	21		30	
Bolivinopsis rosula (Ehrenberg)											212	291	1208	1543	
Guembelitria cretacea Cushman											16				
Guembelina striata (Ehrenberg)	5	2		12		2	7	526	425	543	1257	956	725	771	2
Guembelina glabrans Cushman			1	1						7	16				
Guembelina ultimatumida White	7			113		4	23	6573	9278	14,744	19,975	22,525	15,941	15,427	4
Ventilabrella carseyae Plummer				1				10		14	16				
Bolivinita sp.	1			1		1	2	182	106	86	151	83	145	297	
Eouvigerina hispida Cushman		1							21	14	30	21	24	60	
Pseudouvigerina cretacea Cushman								10		14				30	
Pseudouvigerina cretacea Cushman				19		1	27	849	701	1058	1090	810	821	1602	
Pseudouvigerina seligi (Cushman)				7			6	404	701	400	939	1164	918	2314	1
Buliminella fusiformis Jennings								222	42	514	454	416	290	1063	
Bulimina referata Jennings	2								5	7	16	21	24		
Entosolenia orbignyna (Seguenza)									11	14		42	24	60	
Entosolenia marginata (Walker and Jacob)										14		21			
Virgulina navarroana Cushman							1			14					
Bolivina decurrens (Ehrenberg)										14	16				
Loxostoma gemmum (Cushman)	1			4	1			101	42	143	182	249	290	712	
Ellipsonodosaria pseudoscripta Cushman				2			1							60	
Valvulineria sp.				1						14	16			60	
Gyroidina arkadelphiana Cushman				19							16				
Gyroidina depressa (Alth)	5			1				1234	637	1430	1454	1639	580	1958	
Siphonina prima Plummer				1				162	21	14	23	166	12	178	
Allomorphina trochoides (Reuss)							1		10	11					
Pullenia americana Cushman				1		1	3	586	509	572	615	249	241	415	2
Globigerina lacera (Ehrenberg)	1														
Globigerinella aspera (Ehrenberg)		1		21			23	991	785	1258	2241	1787	628	1187	
Globotruncana fornicata Plummer								20	5		8	83	24	60	
Globotruncana canaliculata (Reuss)				1						7	8	21			
Globotruncana arca (Cushman)				1				10			16				1
Anomalina ammonoides (Reuss)				1					5	14	16	21	12	60	
Anomalina pinguis Jennings				2			1	202							1
Anomalina sp.											30				
Anomalina clementiana (D'Orbigny)											8				
Cibicides sp.								10	11		8	21			
Cibicides harperi (Sandidge)															
TOTAL	22	4	4	209	1	9	103	12,172	13,460	21,135	28,993	30,516	22,088	27,946	13

SAND SURFACE TEXTURES

Studies of the surface textures of sand grains with the electron microscope permit, in some cases, the determination of the environment of their transportation and/or deposition (Krinsley and Takahashi 1962a; in particular, dune and beach sands were distinguished).

Sand grains from Marlboro samples 1, 2, 3, 4A, 4B, 5, 6, and 11 were photographed with the electron microscope at magnifications of about ×5000 using a platinum-palladium replication technique, and show a V-shaped sculpture.

V-shaped topographic patterns are characteristic of modern grains which have been subjected to surf action and have been duplicated experimentally (Krinsley and Taka-hashi 1962b). Further work (unpublished) has shown that V-shaped patterns are occasion-ally found on river grains, but other features are also seen which distinguish these from grains acted upon by surf. In Marlboro sample 1, the V-shaped patterns are not very numerous, and the surfaces of the grains appear to be considerably smoother than many modern beach grains (Krinsley and Takahashi 1962b).

The grains from Marlboro samples 2 and 3 (Mt. Laurel formation) are extremely flat; grains from sample 3 look somewhat like grains of crushed quartz etched in a strongly basic sodium hydroxide solution. The grains from sample 4A show two types of features; the large-scale ones may represent mechanical action, but they are unlike the features seen on modern beach grains (Krinsley and Takahashi 1962b); the smaller

features closely resemble grains etched in sodium hydroxide and in places they seem to have overriden and eliminated the larger textures, suggesting that the etched patterns are of later date.

The grains from sample 4B, close to the Mt. Laurel–Navesink boundary, most closely resemble crushed quartz which has been mechanically agitated in water for about 48 hours simulating beach conditions. It can be shown that when pebbles are added to the crushed quartz under the above conditions, larger surface features result, so the features shown by the grains in sample 4B were probably impressed under conditions where few pebbles were present. A background pattern is also present and may be due to chemical etching, either in sea-water or post-depositionally. The surface textures in samples 4A and 4B are completely different, complementing the sedimentary data and again suggesting a break in sedimentation between the two samples.

Sample 5 again suggests etching, but there is no evidence of shallow-water action. The surfaces of the grains in sample 6 were nearly flat, indicating either that no mechanical action had occurred or, more probably, that the features were subsequently removed. The grains in sample 11 show no V-shapes characteristic of surf action; etching patterns are evident.

It is apparent that electron microscopy will be useful in future sedimentary environmental studies; among possible uses are the differentiation of sedimentary environments as indicated above.

CONCLUSIONS

Interlocked, bored pelecypod shells suggest the presence of currents strong enough to move and interlock the valves; *Cliona* borings indicate periods of quiescence, as do specimens with both valves together in living position. Orientation of belemnites around obstacles with no discernible overall orientation indicates weak and localized currents. The presence of relatively few bored belemnites suggests that few of these fossils were uncovered by current action. In summary, the currents at Marlboro locality were weak, local, and aperiodic.

The crab-claw layer, 4B (Table 1), probably represents shoaling; the presence of crab claws, pebbles, only one foraminifer, and electron micrographs of the sand grains suggests this possibility.

Although juvenile *Exogyra* and *Gryphaea* were not found at Marlboro, it is probable that they were present originally and later eliminated by post-depositional solution. This is indicated by the presence of juveniles along with adults at the Crosswicks Creek locality, and a significant number of pelecypods in living position at Marlboro, together with evidences of solution.

The presence of *Cliona*, a good ecological indicator, suggests clear, silt-free water, full oceanic salinity, and a nearby river mouth where nutrients were provided in quantity.

The benthonic/planktonic foraminiferal ratio in layers 7–13, and large numbers of foraminiferal genera, species, and individuals, suggest depths of from 120 to 300 feet. Floods of planktonic foraminifera are not necessarily unusual at shelf depths; a number of workers (Bandy 1956; Bandy and Arnal 1957; Burnaby 1962) have indicated that up to 70 per cent. planktonic foraminifera can be found here. The large number of foraminiferal individuals also suggests that sedimentation was rather slow in layers 7–13.

The technique of comparing sediment and foraminiferal size frequency distributions

has been used to show that *Guembelina ultimatumida* was sorted after reaching the sea bottom. The study of sand surfaces by electron microscopy is also shown to be valuable in palaeoecological interpretation.

It is felt that the use of as many techniques as possible is advisable in palaeoecological studies so that independent checks on hypotheses are available.

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